LLNL-JRNL-410688

Thick target measurement of the 40Ca(alpha,gamma)44Ti reaction rate

S.A. Sheets, J.T. Burke, N.D. Scielzo, L. Phair, D. Bleuel, E.B. Norman, P.G. Grant, A.M. Hurst, S. Tumey, T.A. Brown, M. Stoyer

February 19, 2009

The Astrophysical Journal

Version February 18, 2009

UCRL-JRNL-400005

Thick target measurement of the ^{40}Ca(α,γ)^{44}Ti reaction rate

S. A. Sheets[1], J. T. Burke[1], N.D. Scielzo[1], L. Phair[2], D. Bleuel[1], J.L. Fisker[1], E.B. Norman[1,2,3], P.G. Grant[1], R. D. Hoffman[1], A.M. Hurst[1], S. Tumey[1], T. A. Brown[1], M. Stoyer[1]

ABSTRACT

The thick-target yield for the ^{40}Ca(α,γ)^{44}Ti reaction has been measured for $E_{\rm beam}$ = 4.13, 4.54, and 5.36 MeV using both an activation measurement and online γ-ray spectroscopy. The results of the two measurements agree. From the measured yield a reaction rate is deduced that is smaller than statistical model calculations. This implies a smaller ^{44}Ti production in supernova compared to recently measured ^{40}Ca(α,γ)^{44}Ti reaction rates.

Subject headings: supernovae: general, nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The radionuclide ^{44}Ti is thought to be produced primarily in the α-rich freeze out in core-collapse supernovae following nuclear statistical equilibrium (1). In the field of γ-ray astronomy most of the attention has focused on the detection of the 68-, 78-, and 1157-keV γ-rays from the ^{44}Ti $\rightarrow$ ^{44}Sc $\rightarrow$ ^{44}Ca decay chain. The 1157 keV γ ray has been observed directly from a point source identified as Cassiopeia A (Cas A) (2). This was later confirmed by the observation of the low-energy ^{44}Sc γ rays using the *BeppoSax* (3) and *INTEGRAL* (4) observatories. Using values for the distance, age, and γ-flux of Cas A, the ^{44}Ti ejected from Cas A was found to be $1.6^{+0.6}_{-0.3}$ μM$_\odot$ (4). This gives an estimated value 2-10 times greater than the ^{44}Ti produced in simulations (6). Although the presence of ^{44}Ti is below detection limits in SN1987A in the nearby Large Magellanic Cloud its current light curve is thought to be powered by the decay of ^{44}Ti. The yield of ^{44}Ti in SN1987A has been estimated to be (100-200)μM$_\odot$ based on the measured yield of ^{56}Co (7). The estimated value for the production of ^{44}Ti in SN1987A is a factor of three greater than expected by models (7). While the mass of ^{44}Ti observed in supernova remnants appears to be underproduced by models, the number of observed sources of ^{44}Ti in all-sky surveys is less than expected from estimates of the Galactic supernova rate and the known ^{44}Ti half life. This discrepancy has led The *et al.* (5) to question whether ^{44}Ti-producing supernova are exceptional.

In order to reduce the model uncertainties associated with the production of ^{44}Ti in supernova, we have focused on the nuclear data uncertainties associated with the main production reaction of ^{44}Ti, the

[1]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94551

[2]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

[3]Nuclear Engineering Department, University of California, Berkeley, California, 94720

^{40}Ca(α,γ)^{44}Ti reaction. The existing experimental results are inconsistent and theoretical estimates are complicated by the suppression of $E1$ $T = 0 \rightarrow 0$ transitions in self-conjugate ($N = Z$) nuclei (8). The ^{40}Ca(α,γ)^{44}Ti reaction has been studied in the past using several techniques. Cooperman *et al* (9) used in-beam γ-ray spectroscopy to measure the capture of α particles on a metallic calcium target in the center-of-mass energy range of $E_{\rm CM}$ = 2.5-3.65 MeV. Nassar *et al.* (10) found the integral cross section in the range $E_{\rm CM}$ = 2.2 - 4.17 MeV by bombarding a He gas target with a ^{40}Ca beam and collecting the recoiling ^{44}Ti in a catcher foil. Accelerator mass spectroscopy was then used to measure the ratio of ^{44}Ti/Ti from the known content of Ti in the catcher foil. Recently, a broader energy range of $E_{\rm CM}$ = 2.11-4.19 MeV was measured using the DRAGON recoil mass spectrometer (11). However, in the energy regime of astrophysical interest ($E_{\rm CM}$ = 2-4 MeV) there exists a factor of two or more difference in the reaction rates between the three measurements.

The aim of the present work is to provide a measurement of the ^{40}Ca(α,γ)^{44}Ti reaction by two separate methods as a check on systematic uncertainties. With in-beam γ-ray spectroscopy a thick target yield measurement was made. The number of ^{44}Ti nuclei produced was then determined by counting low-energy γ rays from the decay of ^{44}Ti. Special attention was devoted to checking the internal consistency of the measurements and to reducing the uncertainties associated with the ^{40}Ca(α,γ)^{44}Ti reaction rate.

2. Nucleosynthesis in an exploding 8.8 $M_\odot$ Star

The ^{40}Ca(α,γ)^{44}Ti reaction was measured at the Lawrence Livermore National Laboratory (LLNL) Center for Accelerator Mass Spectroscopy (CAMS) using a 10 MV FN Tandem Van de Graaff accelerator. A silicon detector was used to calibrate the beam energy by comparing the beam energy as measured with the silicon detector with spectroscopy grade ^{210}Po, ^{252}Cf, ^{241}Am, and ^{230}Th α-sources. From the calibration, the uncertainty in the α-beam energy is $\pm$ 5 keV. The thick target yield was measured at $E_{\rm beam}$ = 4.13, 4.54, and 5.36 MeV beam energies.

For each beam energy a target was manufactured by pressing ^{nat}CaO powder[4] into a copper holder. The powder had a purity of 99.95% (metals basis) but contained ppm concentrations of C and F. To completely stop the beam, each target had a minimum thickness of at least 1.1 mm. The target was mounted on a copper block within the vacuum chamber and tilted at 30° with respect to the beam. The vacuum chamber contained two windows so that the target could be visually monitored.

The target chamber was electrically isolated from the rest of the beam line. Beam current was directly measured from the target chamber. The current integration from the target chamber was checked to a precision of better than 1% using a NIST-traceable precision DC current source. An opposing-pair magnet was attached upstream of the target chamber to suppress the escape of secondary electrons generated by the beam on the target. A summary of the irradiation runs is given in Table 1.

Two 80% HPGe detectors were used to measure the prompt γ-ray yield during irradiation. One detector was 11.4 cm away from the target at 30° with respect to the beam. The location of the second detector was at 15.8 cm and an angle of 99°. The HPGe detector thresholds were set at 125 keV. The average deadtime during a run was ten percent.

The γ-ray energy spectra was accumulated in 8192 channels using two Ortec AD413a ADCs. Efficiency

[4]Obtained from Alfa Aesar, MA, USA

and energy calibrations of the HPGe detectors were made using ^{60}Co, ^{22}Na, ^{137}Cs, ^{54}Mn, and ^{133}Ba NIST-traceable sources with activities known to a 1σ uncertainty of 1%.

The thick target yield for the ^{40}Ca(α,γ)^{44}Ti reaction was deduced from the yield of the $2^+ \to 0^+$ 1083 keV transition which collects most of the strength from ^{44}Ti. The angular distribution of the 1083 keV γ rays with respect to the beam direction is given by $\mathrm{W}(\theta) = \sum_l a_l P_l(\cos\theta)$ with $l = 0, 2, 4$.. The cross section is proportional to a_0 so only this term needs to be determined (12). By placing the detectors at angles for which $P_4(\cos\theta)$ is nearly zero, 30.6° and 109.9°, then a_0 can be determined from a measurement at only two angles.The experimental thick target yield is given by

$$Y = \frac{N_c}{N_p L_t \, \varepsilon_{1083}}, \tag{1}$$

where N_c is the number of counts in the 1083 keV photopeak, N_p is the number of α particles impinging on the target, L_t is the detector live-time fraction, and ε_{1083} is the efficiency of the HPGe detector at 1083 keV. The region near the 1083 keV γ ray is shown in Figure 1 for $E_{\rm beam} = 5.36$ MeV. The 1083 keV photopeak lies on the tail of the 1039 keV ^{70}Ge doppler shifted γ ray excited by fast neutrons primarily from the ^{19}F(α,n) reaction. The background and 1083 keV peak were fit to an error function convoluted with a gaussian, as in Ref. (13). The experimental yield determined from these fits are given in Table 2.

The experimental yield can be related to a theoretical cross section $\sigma(E)$ by the equation

$$Y = \int_0^{E_{beam}} \frac{\sigma(E)}{-dE/dx} dE \tag{2}$$

where $\sigma(E)$ is the energy dependent cross section, and dE/dx is the stopping power for ^{nat}CaO. The dE/dx values for ^{nat}CaO were calculated using the program SRIM (14). Table 2 gives a comparison of the experimental and calculated yields using the NON-SMOKER Hauser-Feshbach ^{40}Ca(α,γ)^{44}Ti cross section (15). The experimental yields are a factor of 2-6 times smaller than the yield calculated from the theoretical cross sections.

The uncertainties from detector efficiencies, deadtime, angular distribution corrections, and beam current integration are tabulated in Table 3. The integrated beam current was cross checked by using the ^{17}O(α,α'γ) and ^{44}Ca(α,α'γ) reactions. The thick-target yield for the ^{17}O(α,α 'γ) reaction that excites the first excited state at 870.8 keV was measured in Ref. (16) at $E_{\rm beam} = 5.486$ MeV. Using Eq. 1, N_p from ^{17}O(α,α'γ) was determined to be $(7.18\pm0.86)\times10^{16}$ after correcting for the difference in beam energy between Ref. (16) and our work. The thick-target yield for the Coulomb excitation of the 1157 keV level in ^{44}Ca was calculated using the program GOSIA (23) and used to infer N_p of $(8.2\pm1.64)\times10^{16}$. This compares well with our beam current integrator which gave a value of 7.2×10^{16} for N_p.

The largest source of uncertainty is the detector efficiency. The efficiency of the detector at 30° was position-sensitive due to the attenuation of γ-rays through the copper target holder. By varying the position

Table 1. Irradiation conditions for the ^{nat}CaO targets.

Irradiation Run	E_{beam} (MeV)	Irradiation time (hours)	Total Charge (μC
1	4.13	6	45808.6
2	4.54	7	46115.8
3	5.36	10	25763.2

of γ-ray sources to match the approximate 1 cm^2 beam spot size the uncertainty in the efficiency was determined. One uncertainty not taken into account in Table 3 are those transitions which bypass the $2^+ \rightarrow 0^+$ 1083-keV transition in ^{44}Ti. A Monte Carlo simulation of the γ-ray cascades from α-capture in ^{44}Ti suggests (20±3)% of transitions bypass the $2^+ \rightarrow 0^+$ transition.

The offline counting of the irradiated target took place at the Low Background Counting facility at LLNL. Only the target irradiated at $E_{\rm beam}$ = 5.36 MeV was counted because the activity of the other targets was estimated to be too low. A HPGe low-energy photon spectrometer (LEPS) detector was used to detect 68- and 78-keV γ-rays from ^{44}Sc decay. The target was placed 2 mm away from the detector face and counted for two weeks. The LEPS detector efficiency at the lines of interest was determined using a 56.6 ± 1.6 nCi ^{44}Ti source. The ^{44}Ti source strength was determined by comparing the 1157 keV from ^{44}Ca to ^{60}Co and ^{22}Na sources previously mentioned using an 80% HPGe detector. By using a ^{44}Ti source to find the efficiency of the LEPS detector the need to correct for the summing of the 68- and 78-kev γ rays was eliminated since the source was the same as the sample.

The yield was found from

$$Y = \frac{A\,T_{\frac{1}{2}}}{N_p \ln 2}, \tag{3}$$

where A is the activity of the irradiated target and $T_{\frac{1}{2}} = 58.9 \pm 0.3$ years is the ^{44}Ti half-life (Ref. (25)).

A simultaneous fit of the peaks in Figure 3 gives an experimental yield of (35.7 ± 0.17) × 10^{-11} ^{44}Ti per α. The uncertainty in the off-line yield takes into account the uncertainty in the efficiency, half-life, integration of beam current, and statistics. This yield is 22% higher than the yield from the online counting and agrees with the estimate that (20±3)% of γ-ray cascades bypass the 1083-keV level and also demonstrates sputtering of the target was minimal during particle bombardment.

The thermonuclear reaction rate can be parameterized in the REACLIB format (15) using the expression $N_A < \sigma\nu >$ (cm^3 s^{-1} mole^{-1}) = exp(130.13 – 4.105x^{-1} + 104.69x$^{-1/3}$ – 263.84x$^{1/3}$ + 11.87x – 0.532x$^{5/3}$ + 130.93ln(x)) where $x = T_9$ in the range $0.1 < T_9 < 10$. The reaction rate found in this work is close to the semi-empircal rate of Rauscher *et al.* (8) and used in the supernovae model of Ref. (27). In Ref. (11) a sensitivity study on the production of ^{44}Ti in the α-rich freeze-out was performed using the available experimental and theoretical reaction rates. The DRAGON and Nassar2006 (10) reaction rates increased the final mass fraction of ^{44}Ti by about 40%. We have also carried out a sensitivity study for the production of radioactive ^{44}Ti using a one zone model. We assume an adiabatic expansion ($\rho \propto$ T^3) starting with pure ^{28}Si in an α-rich freeze out with $T_9 = 5.5$, $\rho_i = 1. \times 10^7$ g cm^{-3} (with the density declining on an e-folding timescale of 0.14 sec). The simulation was halted at charged-particle freeze-out ($T_9 = 0.25$) for a total freeze-out time of 1.31 s. This is identical to the study in (11) but we used a different reaction library (28).

Fig. (**?**) shows the evolution of ^{44}Ti and other select species in our α-rich freezout. Early in the

Table 2. ^{40}Ca(α,γ)^{44}Ti measured and theoretical yields.

E_{beam} (MeV)	Yield (10^{-11})	Theoretical Yield (10^{-11})	Offline Counting (10^{-11})
4.13	2.11 ± 0.14	9.80	
4.54	5.72 ± 0.37	34.3	
5.36	29.2 ± 1.88	61.0	35.7 ± 0.17

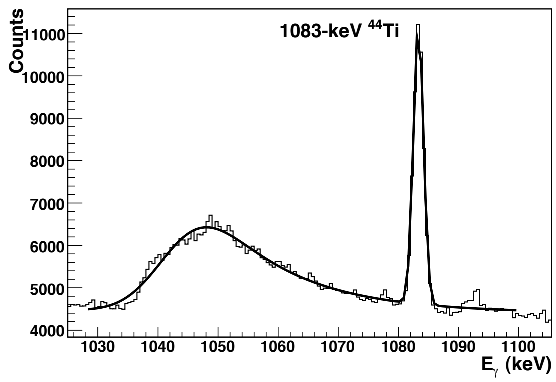

Fig. 1.— Partial HPGe γ-ray spectra at $E_{\mathrm{beam}} = 5.36$ for the detector at 99°

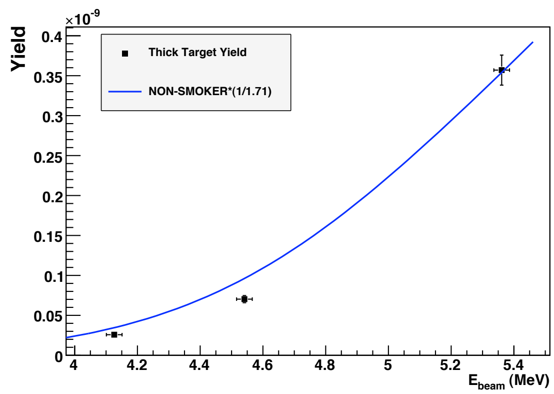

Fig. 2.— The measured integral yield is compared to the Hauser-Feshbach calculations from NON-SMOKER and normalized to the $E_{beam} = 5.36$ MeV off-line counting data point.

Table 3. Compilation of systematic uncertainties for the online measurement (1σ).

Source of uncertainty	Uncertainty
Beam integration	1%
Detector efficiency	7-8%
Deadtime	1%
Angular distribution	4%

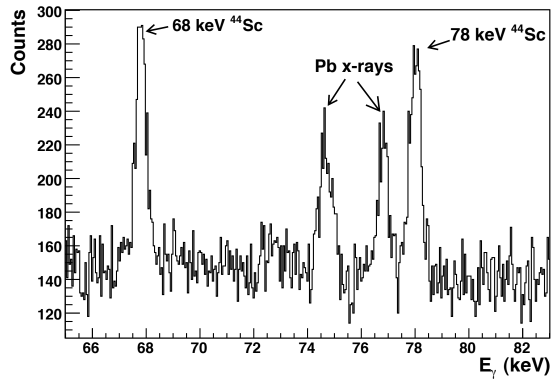

Fig. 3.— γ-ray spectra observed in a two week low background count of the activated target.

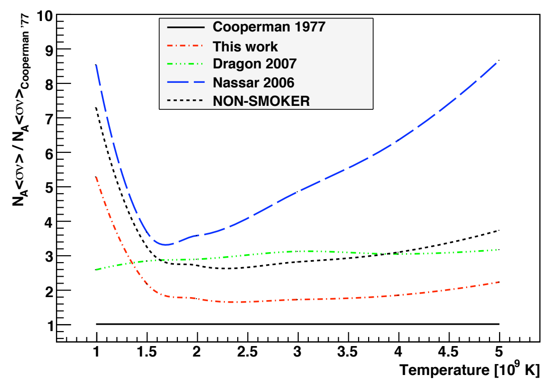

Fig. 4.— Comparison of the ^{40}Ca(α,γ)^{44}Ti reaction rates relative to the measurement of Cooperman *et al.*.

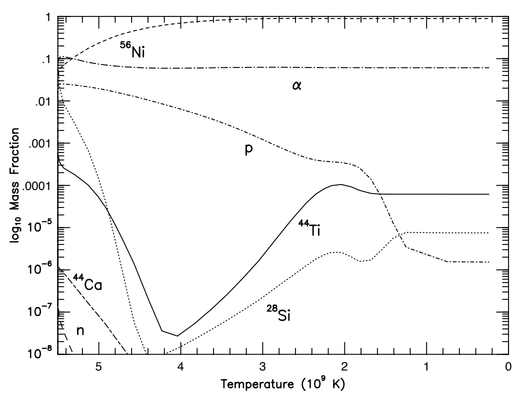

Fig. 5.— Evolution of the mass fraction of some important nuclei in the adiabatic expansion experiencing an α-rich freezeout using our ^{40}Ca(α,γ)^{44}Ti reaction rate.

expansion the composition assumes an NSE distribution producing species in the iron-group as well as ^{44}Ti. During NSE the actual value of the reaction rate is not crucial to the ^{44}Ti abundance. As T_9 drops below 4.0 the mass fraction of ^{44}Ti falls along with ^{28}Si to a value near 10^{-6}, thereafter both increase as α-particles recombine and the value of the principle reaction rates ^{40}Ca$(\alpha, \gamma)^{44}$Ti (production) and ^{44}Ti$(\alpha, p)^{47}$V (destruction) become important (see Fig. 2 of Ref. (26)). The final $\alpha-$particle mass fraction was 0.06.

The sensitivity of ^{44}Ti production in our simulations for different ^{40}Ca$(\alpha,\gamma)^{44}$Ti rates is shown in Fig. 5. The final amount of ^{44}Ti produced scales with the value of the reaction rate at $T_9 = 2.0$, where in the simulations ^{44}Ti reached half its final value. Our rate suggests that the results from the most recent experiments are over-estimating the amount of ^{44}Ti produced in this type of freeze-out. Interestingly, we agree most closely with the semi-emperical result of (15), which takes into account the results of earlier experiments of $\alpha-$capture on self-conjugate nuclei.

We thank Irshad Ahmad and John Greene of Argonne National Laboratory for preparing the ^{44}Ti calibration source. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, the DOE Scientific Discovery through Advanced Computing program (DC-FC02-01ER41176), and by the University of California, Lawrence Berkeley National Laboratory under Contract No. W-7405-Eng-48.

REFERENCES

S.E. Woosley and T.A. Weaver, Astrophys. J. Suppl, Ser, **101**, 181 (1995).

A. F. Iyudin *et al.*, Astron. Astrophys. **284**, L1 (1994).

J. Vink *et al.*, Astrophys. J., **560**, L79 (2001).

M. Renaud *et al.*, Astrophys. J. **647**, L41 (2006).

L.-S The, *et al.*, Astron. Astrophys. **450**, 1037-1050 (2006).

S.E. Woosley and R.D. Hoffman, Astrophys. J., **368**, L31 (1991).

R. Diehl *et al.*,, Nucl. Phys. A, **A777**, 70 (2006).

T. Rauscher *et al.*, Nucl. Phys. **A675**, 695 (2000).

E.L. Cooperman *et al.*, Nucl. Phys. A, 284 (1977).

H. Nassar *et al.*, Phys. Rev. Lett. **96**, 041102 (2006).

C. Vockenhuber *et al.*, Phys. Rev. C, **76**, 035801 (2007).

P. Dyer *et al.*, Phys. Rev. C, **23**, 1865 (1981).

E. Gete *et al.*, Nucl. Instr. Methods Phys. Res. Sect. A **388**, 212 (1997).

J.F. Ziegler, *The Stopping and Range of Ions in Solids*, http://srim.org (2007).

T. Rauscher and F. Thielemann, At. Data Nucl. Data Tables **79**, 41 (2001).

H.H. Hsu, Nucl. Instr. Meth., **193**, 383 (1982).

D. D. Clayton, Nature, **257**, 36 (1975).

F. A. Iyudin *et al.*, Astro. Lett. Comm., **38**, 383 (1999).

L. R. Nittler *et al.*, Astrophys. J., **462**, 31 (1996).

C. Dupraz *et al.*, Astron. Astrophys., **324**, 683 (1997).

N. Ryezayeva *et al.*, Phys. Rev. Lett. **89**, 272502 (2002).

I. Ahmad *et al.*, Phys. Rev. C, **74**, 065803 (2006).

T. Czosnyka *et al.*, Am. Phys. Soc., **28**, 745 (1983).

J.K. Bair and H.B. Willard, Phys. Rev., **128**, 299 (1963).

I. Ahmad *et al.*, Phys. Rev. C, **74**, 065802 (2006).

L.S. The *et al.*, Astrophys. J., **504**, 500 (1998).

T. Rauscher *et al.*, Astrophys. J. **576**, 323 (2002).

R. D. Hoffman *et al.* (2002). RateTable v. 8.2, http://physci.llnl.gov/Research/RRSN/

This preprint was prepared with the AAS LATEX macros v5.0.

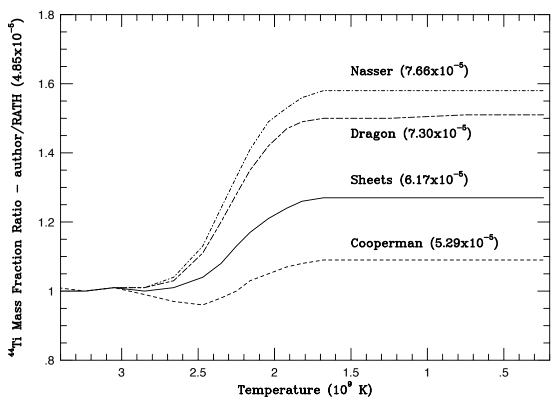

Fig. 6.— ^{44}Ti mass fraction as a function of temperature for different ^{40}Ca(α,γ)^{44}Ti reaction rates relative to CITE.